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TITLE – ALSEP Heat Flow Experiment Method of Gradient Measurement

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AUTHOR(S) – P. J. Hickson

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ABSTRACT

The theory behind the method of temperature gradient measurement in the Heat Flow Experiment of the Apollo Lunar Surface Experiment Package (ALSEP), not previously available in concise form, is presented and the experiment calibration briefly discussed. It is, therefore, made clear that the experiment is theoretically sound and that the calibration program is adequate and contains no duplication of effort.

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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

In a typical heat flow experiment a temperature difference might be measured as a voltage at the electronics output. As such, a "total system calibration" prior to emplacement would be required and would usually be given as a curve of temperature difference versus voltage. The stability of such a system would be difficult to guarantee for the 1 year ALSEP lifetime, since amplifier gain drifts or zero offset due to noise at the input would destroy the calibration. The scheme is, therefore, <u>not</u> used in the ALSEP Heat Flow Experiment (HFE).

The fact that the HFE is not given a "total system calibration" (although the term "calibrating the electronics" is sometimes incorrectly used) has caused some minor confusion as to purpose and function of the calibration and test program for the HFE. This minor confusion is occasioned at least in part by the fact that theory behind the HFE temperature gradient measurement is not readily available in concise form. It is the purpose of this memorandum to correct this deficiency.

In the memorandum we will first exhibit the relevant equations and discuss the sequence of measurements. This will be followed by a brief discussion of the "calibration and test" program after which it will be clear that the HFE calibration program is adequate and contains no duplication of effort.

2.0 EXPERIMENT CONFIGURATION AND BRIDGE EQUATIONS

Consider the bottom half of a HFE probe.* This section contains two sensor cans, a distance of 55 cm apart, each containing two platinum resistance thermometry elements (each nominally 500 ohms). The four resistors are hard-wired into a bridge as shown in Figure 1. In general, the two sensor cans will be at different temperatures,

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*Identical to the top half. The term probe is applied to the "sausage-like" assemblage in one bore-hole. Each half of a probe then contains one gradient bridge, two thermal conductivity heaters and two special thermal conductivity sensors.

[redacted]

the difference being about 0.050 K° in a "typical" experiment, and which should be measured to about ± 0.003 K°. The temperature gradient then, is simply the measured temperature difference, Δt, divided by 55 cm.

As indicated in Figure 1 and its accompanying equations both the temperature difference, Δt, and the temperature, t, of one sensor can, may be measured by successive measurement of the relative bridge unbalance, V, and the equivalent bridge conductance G. The temperature of the other sensor unit is, of course, $t+\Delta t$. Since each platinum element is characterized by 4 constants, the bridge is characterized by 16 constants. In general, G and U are very complicated functions of t and Δt, but nevertheless these can be inverted to give equations (4) and (5). Note that, for a successful measurement, Δt is required to very high resolution, and since the bridge sensitivity is temperature dependent, t must also be measured, but only to about ± 0.1 °K. Since the expected Δt values are smaller than 0.1 °K, $\bar{t}$ may be regarded as the "average bridge temperature," i.e., equation (5) can be regarded as being relatively independent of U in the experiment (but not in the bridge calibration). In practice, dynamic range is improved if the resistors are matched so that the relative bridge unbalance U is zero when $\Delta t=0$ at some reference (mid-point) temperature. U is then approximately proportional to Δt. It should be clearly emphasized that the equivalent bridge resistance 1/G is <u>not</u> regarded, and cannot be regarded, as a pseudo-platinum thermometry element described by equation (1a). Rather, equation (3) or its inverse, equation (5), must be used to determine t from a measurement of G.

In the experiment Δt is determined by successive measurement of U and G and use of equation (4). Actually, in the ALSEP sequence, it is the bridge unbalance V and the bridge excitation voltage E (about 10 volts) which are measured and transmitted to earth (so that U is determined during the data analysis) and then about 4 seconds later the bridge current I and excitation voltage E are measured, giving G. The bridge current is measured by measuring the drop across a known temperature-insensitive precision resistor R_p. Note that since the parameter U and G are <u>ratios</u>, they are independent of gain changes and reference voltage changes in the HFE electronics. Thus, the HFE electronics need only be stable for longer than 4 seconds, the length of the measurement cycle. Slow gain drifts due to component aging or hysteresis are, therefore, tolerable. However, we must go one step further.

We have described a d.c. measurement system and such systems are susceptible to zero offset so that the voltage actually measured is not V but $(V-E_{offset})$ where E_{offset} is an equivalent noise voltage produced by currents flowing in the amplifier input stage through the HFE bridge. Such error currents do not change sign when the input signal is reversed and so, for example, do not perturb a.c. measurements. These offset errors are therefore eliminated in the HFE by a measurement sequence technique using bipolar excitation. (Why a measurement is termed "bipolar" rather than "alternating current" is largely a matter of semantic taste but some equipment differences are obvious since bipolar or d.c. implies that the circuit elements are frequency insensitive.) In the HFE the excitation voltage is actually a bipolar (i.e., positive then negative) square wave, of sufficiently short duration (about 2.3 milliseconds) that Joulian self-heating of the thermometry elements results in negligible temperature changes. Thus E_+ is applied to the bridge and E_+, V_+ measured, followed immediately by application of E_- and measurement of E_- and V_-. About 4 seconds later E_+, I_+, and E_-, I_- are measured. Thus, for example, the bridge unbalance is now given by

$$U = \frac{V_+ - V_-}{E_+ - E_-} \qquad 2(b)$$

which is seen to be independent of offset errors. (In equation 2b V_- is a negative number.)

3.0 ANALOG-TO-DIGITAL CONVERTER

We now briefly describe the operation of the analog-to-digital converter. Referring to Figure 2, we see that the sample voltage, V_{in}, must be in the range -10 to +10 volts. The reference voltage (about 10 volts) is added to this immediately so that a positive voltage of 0 to 20 volts must be digitized. On the right in Figure 2 is a sketch of a ladder circuit. The ladder has a property such that each stage produces at the ladder output a voltage which is 1/2 of that produced at the ladder output by the stage immediately preceding it (to the left). This voltage is produced at the ladder output if the switch for that step is closed. In the digitizing sequence each switch is closed in turn, starting with the most significant switch at the left, and the error detecting circuit then decides if that switch is to remain latched or if it should drop out. At the end of the entire sequence the condition of the switches gives the digitized voltage number, a binary number with a 1 for each closed switch and a 0 for each open switch. Thus, a voltage binary number B, returned from ALSEP, is

$$B = \sum_{n=0}^{12} \frac{a_n}{2^n} = \frac{V_{in} + AE_{ref}}{E_{ref}} \qquad (7)$$

where a_n is a binary digit, 1 or 0. The binary number B then represents the ratio of the voltage to be digitized to the reference voltage of the ADC. Returning to equation 2b we see that U is formed from 4 binary numbers obtained from ALSEP and hence is given explicitly as the equation:

$$U = \frac{\left(\frac{V_+ + AE_{ref}}{E_{ref}}\right) - \left(\frac{V_- + AE_{ref}}{E_{ref}}\right)}{\left(\frac{E_+ + AE_{ref}}{E_{ref}}\right) - \left(\frac{E_- + AE_{ref}}{E_{ref}}\right)} \qquad 2(c)*$$

where V_- and E_- are negative numbers. It is clear then that the experimental parameter U is independent of gain changes, changes in the reference voltage of the ADC, and amplifier d.c. offset, provided only that these changes are small over a period of 4 seconds. We have here traded ADC bits for ADC stability since, to get the experimental answer U to 11 bit accuracy ($\pm$ 1/2 part in 2048) it is necessary to make 4 measurements, each to 13 bit accuracy. The digitizing error of the ADC is, of course, $\pm$ 1/2 bit in a single digitizing sequence.

4.0 DISCUSSION

From the above analyses it is clear that after mating the probe with its electronics one requires only that the electronics' gain settings and the like be trimmed to the proper dynamic range since the method of measurement eliminates any electronic effects from the experimental parameters U and G. Terms such as "calibrating the electronics" or "total system calibration" do not apply to this experiment and hence do not describe any operations in the HFE test and calibration schedule. The HFE gradient measurement is thus calibrated by

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*Since AE_{ref} is an offset voltage we include in it all offset error voltages as well.

Rosemount Engineering Corp.*, who calibrate the probe bridges, and the calibration is checked by A. D. Little from data taken during their measurement of the probes' thermal characteristics.

The primary function of the A. D. Little "probe test and calibration program" is to measure the thermal properties of the probe as a function of frequency (at steady state and 300 nanohertz**). This data will be useful for making minor corrections to the gradient data and is indispensable for interpreting the thermal conductivity data. The former results from the fact that the temperature gradient in the probe might be as much as 10% smaller than the ambient lunar gradient, due to the shorting effect of the probe, if the probe thermal conductivity is significantly higher than that of the moon. The ADL program consists of: (a) a direct measurement of the thermal conductivity of the probe, by applying a known temperature gradient to it and taking gradient data. This data incidentally will serve as a confirmation that the probe is capable of measuring a gradient although the data is not of high accuracy since such is not necessary for the conductivity measurement. <u>This procedure should not be construed as a duplication or possible replacement of the high precision gradient calibration procedure used by Rosemount</u>; and (b) an indirect measurement of the thermal conductivity, heat capacity and thermal relaxation times of the probe by using the probe to measure the (known) thermal conductivity of three materials in vacuum. This procedure lends itself well to characterizing the probe by an equivalent thermal circuit or model and so is sometimes referred to as "calibrating the thermal conductivity measuring capability of the probe."

Lastly, and pertinent to this memorandum, it has been suggested that the HFE performance should be specified by demanding a specified percentage accuracy on the heat flow value measured. We believe, however, that the wide dynamic range covered by the experiment demonstrates that such a specification is unnecessary except, perhaps, as a curve. It is therefore the current practice to specify the resolution of each component sensor at the best level presently considered feasible. In this way the present specification scheme assures the Principal Investigator of the most accurate data attainable with the present experiment configuration over the widest dynamic range feasible.

5.0 <u>SUMMARY</u>: The bridge equations for the HFE gradient measurement are two equations in two unknowns, Δt and t. Therefore two experimental numbers are required to determine Δt. In the HFE measurement sequence, bipolar bridge excitation is used to

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*This high precision calibration involves applying 5 Δt values to the bridge at each of 5 temperatures t so the 25 measurements more than adequately determine the 16 bridge constants.

**i.e., $\sim$ 1 cycle/mo

eliminate offset error and experimental numbers are calculated as measurement ratios to eliminate gain drift errors. Thus, eight experimental measurements are required to measure Δt once, and Δt so obtained is entirely independent of the performance of the electronics, provided only that the electronics is stable for 4 seconds, the measurement cycle time.

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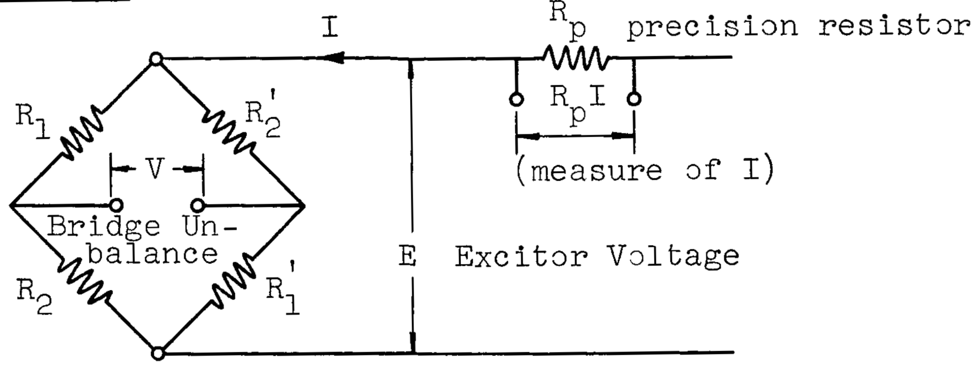
Attachments
Figures 1 & 2

FIGURE 1: HFE Bridge Circuitry and Equations



Platinum resistance thermometry elements R_1 and R_1' are packaged together and are at temperature t, R_2 and R_2' are together at $t+\Delta t$. $t \simeq -53°C$ (220 K°)

For the ith resistor

$$R_i(t) = R_{0i}[1+A_i t+B_i t^2+C_i(t-100)t^3] \cdots\cdots \quad (1a)$$

$$\left.\begin{array}{l} A = +\ 3.98 \times 10^{-3}/\text{deg C}, \quad B = -\ 5.86 \times 10^{-7}/\text{deg}^2, \\ C = -\ 4.33 \times 10^{-14}/\text{deg}^4 \end{array}\right\} \cdots\cdots \quad (1b)$$

$$R_{0i} \approx 500 \text{ ohms.}$$

Bridge Equations:

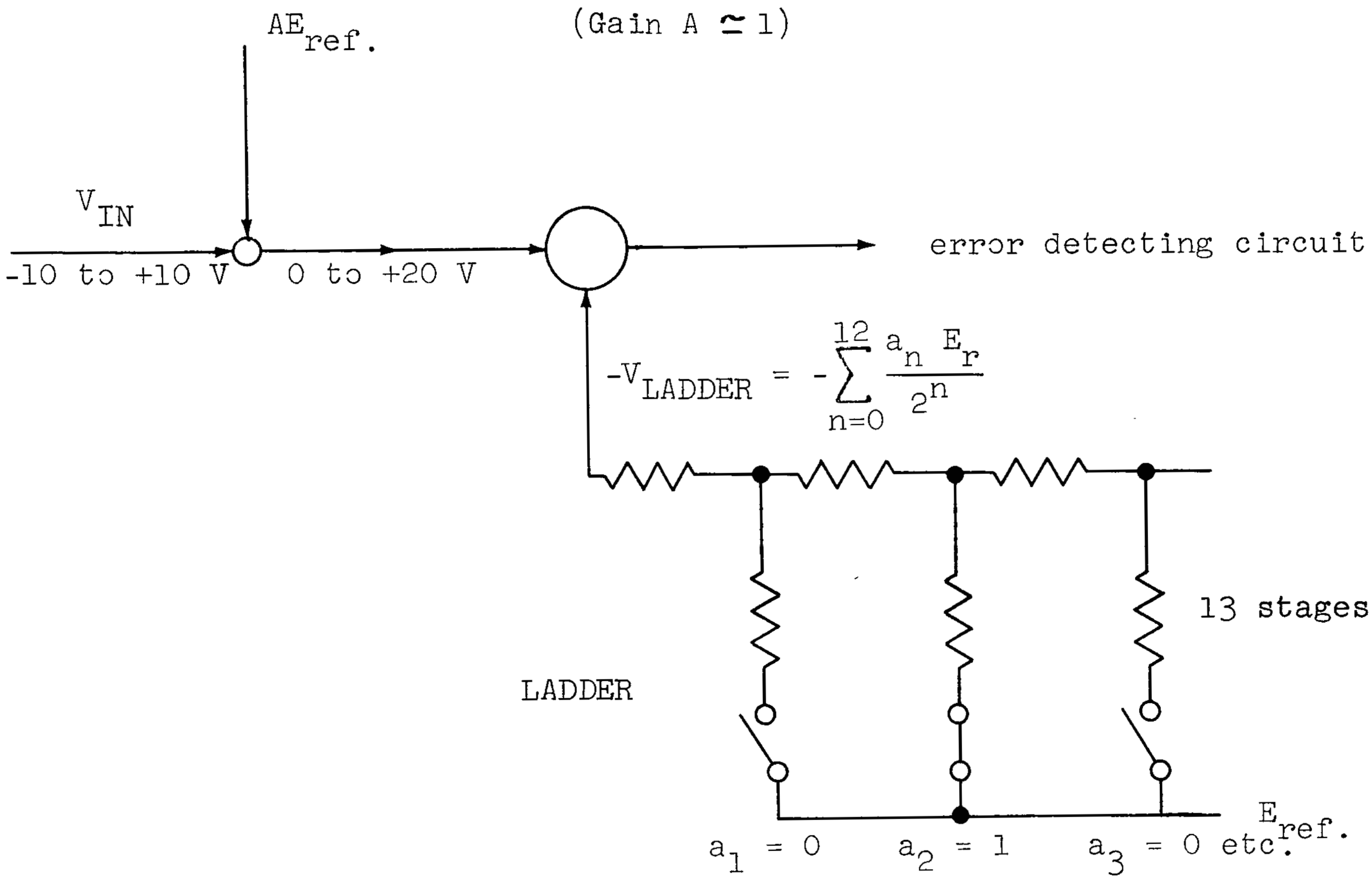
$$U = \frac{V}{E} = \frac{R_1}{R_1+R_2} - \frac{R_2'}{R_1'+R_2'} = \text{function of 16 constants and } \Delta t,\ t \cdots\cdots \quad (2a)$$

$$G = \frac{1}{R_{\text{equivalent}}} = \frac{I}{E} = \frac{1}{R_1+R_2} + \frac{1}{R_1'+R_2'} = \text{function of 16 constants and } \Delta t\ ,\ t \cdots\cdots \quad (3)$$

$$\therefore\ \Delta t = \Delta t\ (U,\ G,\ 16 \text{ constants}) \quad \cdots\cdots \quad (4)$$

$$t = t\ \ (U,\ G,\ 16 \text{ constants}) \quad \cdots\cdots \quad (5)$$

FIGURE 2: A to D Converter Scheme



The error detecting circuit produces an output if the voltage at its input is greater than zero, i.e.,

$$(V_{IN}+AE_{ref}) - V_{LADDER} > 0 \qquad (6)$$

Reading the condition of the switches gives the digital voltage value. The binary digits a_n then form a binary number B which is the ratio of the voltage digitized to the reference voltage E_{ref}, i.e.,

$$B = \sum \frac{a_n}{2^n} = \left(\frac{V_{IN}+AE_{ref}}{E_{ref}} \right) \qquad (7)$$